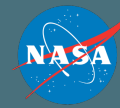




Direct Metal Laser Sintering of Inconel 718

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The Material

Inconel 718 is used widely in aerospace due to its excellent thermal and strength properties while retaining a high degree of reliability in extreme conditions. It is particularly resistant to oxidation and corrosion. The Inconel 718 super alloy we tested is composed primarily of Nickel, Chromium, and Iron, with lesser amounts of Niobium, Molybdenum, Titanium, and Vanadium.



The Problem

While Inconel 718 is well suited for high temperature applications, it is a difficult material to machine and weld. Inconel responds to traditional machining techniques with rapid work hardening, which subsequently tends to damage machining tools. When welding Inconel 718, segregation of alloying components in the heat affected zone around the weld compromise material strength.

The Solution



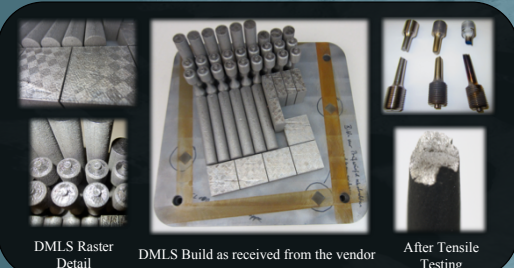
Direct Metal Laser Sintering (DMLS) of geometrically complex Inconel parts largely removes the need to machine and weld. This means that stronger and more reliable Inconel components can be manufactured in-house, faster and at a lower cost.

Objectives

The absolute highest quality DMLS Inconel 718 samples were requested from vendors with DMLS manufacturing capabilities. These samples underwent a comprehensive suite of material testing including Tensile, Low Cycle Fatigue, High Cycle Fatigue, Fracture Toughness, Fatigue Crack Growth Rate, and Creep. DMLS Inconel 718 was compared in each characteristic to traditional wrought Inconel 718, and we aimed to answer the following questions:

- How does build orientation (stacking in x, y, or z axis) impact material properties?
- What minimum surface roughness can be achieved without post-processing of DMLS builds?
- How does surface roughness impact the fatigue strength (life expectancy) of DMLS products?
- How does the microstructure of DMLS products compare to wrought Inconel 718?

Ultimately, answering these questions will help establish industry standards for DMLS manufactured parts.



Microscopy & Heat Treatment

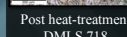
➤ Initial tensile results from as-built samples were sub-par, far less than strengths seen in wrought Inconel. Study found that the vendors had stress-relieved the samples at temps above ASTM standards. To correct this, all of the samples were homogenized via a heat treatment at 2125°F. This freed strengthening elements Niobium and Titanium, which were tied up in the solidification process.



Vendor 1 & 3:
Grains are visibly stacked and elongated.



Vendor 2: Grains are equiaxed much like wrought 718.



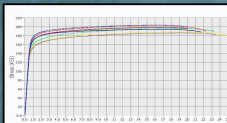
Post heat-treatment DMLS 718



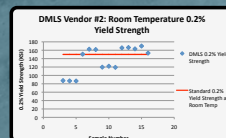
Wrought 718

➤ Afterward, sample hardness increased 30% to acceptable levels. Additionally, DMLS 718 microstructure (left) looked very similar to wrought microstructure (right) on samples from all vendors. Grains were uniaxed, with roughly equal diameters in all directions.

Tensile Testing



Tensile Testing was performed on a standard MTS Tensile tester, outfitted with a suspended ATS tube furnace to fit over the sample. Strain was measured with an extensometer for room temperature samples, and a ceramic strain gauge extensometer for the high temperature tests.



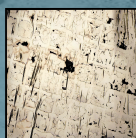
Tensile Test Results suggest that DMLS Inconel 718 samples provided by all vendors matched or rivaled the properties of Wrought Inconel 718 in regards to Elastic Strain Modulus, 0.2% Yield Strength, and Ultimate Yield Strength across all temperatures tested.

Serrations in the 800F Tensile Test Results

Serrations in the Stress-Strain curve post-yielding can be attributed to Dynamic Strain Aging (DSA) of the material within a certain temperature regime, and has been observed in other Inconel Alloys. The work-hardening mechanism is a result of the pinning of lattice dislocations due to the diffusion of solute elements into the matrix of the material.

To further confirm that DSA is an inherent material property and not unique to DMLS samples, additional tests of wrought Inconel 718 were performed at 800°F. After serrated results were observed, testing of DMLS samples resumed.

Surface Roughness

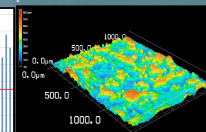
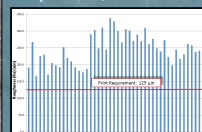


The DMLS J-2X Discharge U-Duct currently struggles to meet traditional standards for surface smoothness. This results from the build methodology. As each layer is added, a support lattice must be utilized to prop up hovering sections. Where these supports are removed, dimples are left behind on the surface (see left). Exterior surfaces can be polished to meet smoothness standards, but tight interior regions cannot be easily reached.

➤ We need to know how this roughness impacts the product's structural integrity.

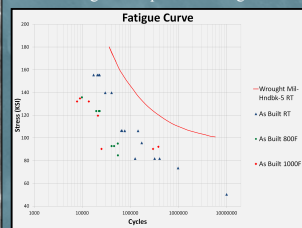
Surface Roughness & Fatigue Testing

Surface roughness is known to have a non-trivial effect on fatigue strength of wrought materials. Roughness creates facial areas with a high stress gradient, which serve as ideal points of origin for fracture, and subsequently premature failure of the material. We requested DMLS builds with a maximum surface roughness of 125µin, and none of the vendors succeeded in meeting this requirement, as shown in the plot on the left.



This 3D surface plot of as-built DMLS samples shows individual powder grains protruding from the surface that define the minimum resolution of DMLS builds.

To understand the effect of roughness on material strength, we performed High Cycle Fatigue (HCF) Tests. The MTS Tensile Tester was programmed to cycle at 40Hz between an upper and lower boundary tensile stress loading of 35% to 75% of Yield Strength. Temperatures ranged from RT to 1000°F.



A fatigue curve is extrapolated using each HCF test result as a single data point. The red line represents the ASTM standard fatigue curve for wrought Inconel 718, and is compared with the as-built DMLS data points to the left. Fatigue Strength was reduced in the rough, as-built DMLS samples, shown by the suppressed HCF data points.

Ultimately we will fatigue test the post-machined, smooth DMLS samples and compare with the as-built DMLS samples to determine whether the reduction in the fatigue strength of DMLS Inconel 718 can be attributed to surface roughness, or is inherent to DMLS parts regardless of surface roughness.

Conclusion

This study shows that Direct Metal Laser Sintering Technology has made substantial progress towards replicating the bulk material characteristics of traditionally manufactured Inconel 718. However, elements such as surface roughness, heat treatment, structural build features, and parts with particularly tight tolerance requirements still present hurdles to overcome before DMLS will become a comprehensively superior manufacturing method. DMLS does succeed in significantly reducing the cost of manufacturing parts with complex geometries.

In the near-term, DMLS of Inconel 718 shows promise for a variety of NASA applications, especially in the J-2X engine. It is currently at a Manufacturing Readiness Level (MRL) 6, and material specifications must be fully established before progressing to MRL-7. This project has identified final DMLS build specifications such as heat treatment through microscopy studies, and hopes to define surface roughness tolerances to assist this MRL transition.

Future Work

- What differences in build parameters did Vendor #2 utilize to eliminate the grain boundary issues observed in the other two vendors?
- When Marshall Space Flight Center receives its DMLS machine, will we be able to determine DMLS build parameters and repeat industry success?
- How much microstructural difference should be tolerated in regards to Quality Control of DMLS builds?

References

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